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# Search for anomalous single top quark production in association with a photon in pp collisions at $\sqrt{s} = 8$ TeV

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## Abstract

The result of a search for flavor changing neutral currents (FCNC) through single top quark production in association with a photon is presented. The study is based on proton-proton collisions at a center-of-mass energy of 8 TeV using data collected with the CMS detector at the LHC, corresponding to an integrated luminosity of  $19.8 \text{ fb}^{-1}$ . The search for  $t\gamma$  events where  $t \rightarrow Wb$  and  $W \rightarrow \mu\nu$  is conducted in final states with a muon, a photon, at least one hadronic jet with at most one being consistent with originating from a bottom quark, and missing transverse momentum. No evidence of single top quark production in association with a photon through a FCNC is observed. Upper limits at the 95% confidence level are set on the  $t\mu\gamma$  and  $tc\gamma$  anomalous couplings and translated into upper limits on the branching fraction of the FCNC top quark decays:  $\mathcal{B}(t \rightarrow u\gamma) < 1.3 \times 10^{-4}$  and  $\mathcal{B}(t \rightarrow c\gamma) < 1.7 \times 10^{-3}$ . Upper limits are also set on the cross section of associated  $t\gamma$  production in a restricted phase-space region. These are the most stringent limits currently available.

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# 1 Introduction

Evidence of physics beyond the standard model (SM) can be sought in measurements of the rates of flavor changing neutral currents (FCNC) in the top quark sector. Within the SM, top quark FCNC transitions are extremely suppressed by the GIM mechanism [1]. The predicted branching fraction ( $\mathcal{B}$ ) for  $t \rightarrow u\gamma$  and  $t \rightarrow c\gamma$  decays are approximately  $10^{-14}$  [2]. However, an enhancement of several orders of magnitude is predicted in some extensions of the SM, resulting in branching fractions observable at the LHC in some cases [3, 4]. Therefore, observation of these rare top quark decay modes would be indicative of physics beyond the SM.

Searches for FCNC  $tu\gamma$  and  $tc\gamma$  interactions have been carried out by several experiments, with as yet no indication of a signal. The measured upper limits at the 95% confidence level (CL) on the branching fraction of  $t \rightarrow q\gamma$ , with  $q$  representing an up or charm quark, through single top quark production are 4.1% (L3) [5], 0.29% (ZEUS) [6], and 0.64% (H1) [7]. The 95% CL limit set by the CDF experiment through top quark pair production is  $\mathcal{B}(t \rightarrow q\gamma) < 3.2\%$  [8].

The most general effective Lagrangian up to dimension-six operators,  $\mathcal{L}_{\text{eff}}$ , used to describe the FCNC  $tq\gamma$  vertex has the following form [9]:

$$\mathcal{L}_{\text{eff}} = -eQ_t \sum_{q=u,c} \bar{q} \frac{i\sigma^{\mu\nu} q_\nu}{\Lambda} (\kappa_{tq\gamma}^L P_L + \kappa_{tq\gamma}^R P_R) t A_\mu + \text{h.c.}, \quad (1)$$

where  $e$  and  $Q_t$  are the electric charges of the electron and top quark, respectively,  $q_\nu$  is the four-momentum of the photon,  $\Lambda$  is an effective cutoff, which conventionally is taken as the top quark mass,  $\sigma^{\mu\nu} = \frac{1}{2}[\gamma^\mu, \gamma^\nu]$ , and  $P_L$  and  $P_R$  reflect, respectively, the left- and right-handed projection operators. The strengths of the anomalous couplings are denoted by  $\kappa_{tq\gamma}^{L,R}$ . No specific chirality is assumed for the FCNC interaction of  $tq\gamma$ , i.e.,  $\kappa_{tq\gamma}^L = \kappa_{tq\gamma}^R = \kappa_{tq\gamma}$ . In the SM, the values of  $\kappa_{tu\gamma}$  and  $\kappa_{tc\gamma}$  vanish at the lowest tree level. A fully gauge-invariant effective-Lagrangian approach for parametrizing the top quark FCNC interactions has been studied in Ref. [10]. The FCNC effective Lagrangian can be used to calculate both the branching fractions of the  $t \rightarrow q\gamma$  decays and the cross sections for the production of a top quark in association with a photon.

The top quark FCNC processes can be probed through either top quark production or decay. In this paper, we examine the associated production of a single top quark and a photon, which is sensitive to the anomalous  $tq\gamma$  FCNC coupling. The difference between quarks and antiquarks in the parton distribution functions (PDF) of the proton in the presence of a finite  $tu\gamma$  coupling leads to an asymmetry between top and anti-top quark production rates. No asymmetry is expected for  $tc\gamma$ , because of the similar charm and anti-charm quark contents in the proton. This would allow a distinction between the  $tu\gamma$  and  $tc\gamma$  signal scenarios if these processes were observed [11]. Better sensitivity to the  $tu\gamma$  coupling is expected because the up quark PDF in the proton is larger than that of the charm quark.

Within the SM, top quarks can also be produced in association with a photon. This proceeds through the radiation of a photon from the initial- or final-state particles in  $t$ -channel,  $s$ -channel, and  $W$ -associated production of single top quarks. These processes are treated as backgrounds in this analysis.

We search for FCNC interactions at the  $tu\gamma$  and  $tc\gamma$  vertices by looking for events with a single top quark and a photon in the final state, where the top quark decays into a  $W$  boson and a bottom quark, followed by the decay of the  $W$  boson to a muon and a neutrino. The final state includes  $W^\pm \rightarrow \tau^\pm \nu_\tau$  events in which the  $\tau$  lepton decays to  $\mu\nu$ . We focus on this particular leptonic decay because it has a very clean signature. Figure 1 illustrates the lowest-order dia-

gram for this  $t\gamma$  process including the muonic decay of the W boson from the top quark decay. The FCNC vertex is identified by a filled circle.

One of the distinctive signatures of the signal is the presence of a high transverse momentum ( $p_T$ ) photon in the final state. The photon is expected to have large transverse momentum, owing to its recoil from the heavy top quark. The analysis is performed using events with a muon, a photon, at least one hadronic jet, with at most one being consistent with originating from a bottom quark, and missing transverse momentum. The results are compared with leading-order (LO) and next-to-leading-order (NLO) calculations of the FCNC signal production cross section based on perturbative quantum chromodynamics (QCD) [12].

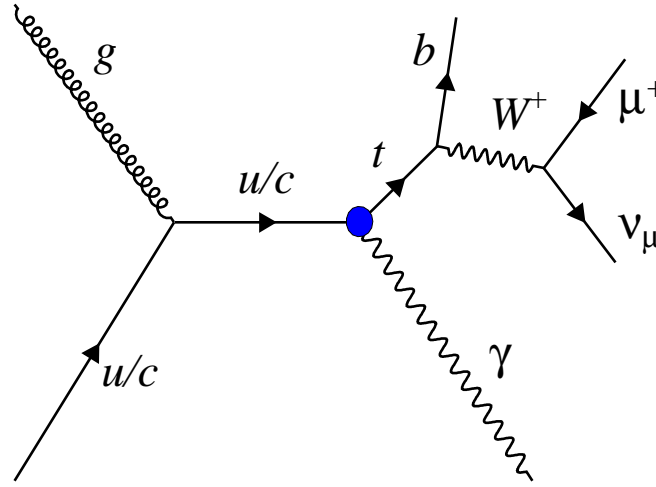


Figure 1: Lowest-order Feynman diagram for single top quark production in association with a photon via a FCNC, including the muonic decay of the W boson from the top quark decay. The FCNC vertex is marked as a filled circle.

## 2 The CMS detector

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. A silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter (ECAL), and a brass and scintillator hadron calorimeter (HCAL), each composed of a barrel and two endcap sections are contained within the superconducting solenoid volume. Extensive forward calorimetry complements the coverage provided by the barrel and endcap detectors. Muons are measured in gas-ionization detectors embedded in the steel flux-return yoke outside the solenoid.

The first level of the trigger system, composed of custom hardware processors, is designed to select the most interesting events in less than  $4\ \mu\text{s}$ , using information from the calorimeters and muon detectors. The high-level trigger processor farm further decreases the event rate from about 100 kHz to less than 1 kHz, before data storage.

A more detailed description of the CMS detector, together with a definition of the coordinate system and kinematic variables used in this analysis, can be found in Ref. [13].

### 3 Data and simulation samples

The analysis is based on a data sample of proton-proton collisions at a center-of-mass energy of 8 TeV, corresponding to an integrated luminosity of  $19.8 \text{ fb}^{-1}$ , collected with the CMS detector at the CERN LHC.

Monte Carlo (MC) simulated signal samples of  $pp \rightarrow t\gamma \rightarrow W^\pm b\gamma \rightarrow \ell^\pm \nu_\ell b\gamma$ , with  $\ell$  representing  $e$ ,  $\mu$ , or  $\tau$  leptons, are generated with the PROTONS 2.0 generator [14], with a minimum  $p_T$  requirement of 30 GeV for the associated photon. PROTONS is a LO generator for single top quark and  $t\bar{t}$  production that includes anomalous top quark couplings.

To study the response of the analysis to the signal and to processes with potentially similar final-state signatures, simulated event samples of  $t + \gamma$ ,  $t\bar{t}$ ,  $t\bar{t} + \gamma$ ,  $W\gamma$ +jets,  $Z\gamma$ +jets, Drell-Yan,  $W$ +jets, and  $WW\gamma$ +jets events are generated using the LO MADGRAPH 5 generator [15]. Diboson samples ( $WW$ ,  $WZ$ , and  $ZZ$ ) are generated using PYTHIA 6 [16]. Single top quark events from  $tq$ -,  $t\bar{b}$ -, and  $tW$ -channel are generated with the NLO POWHEG 1.0 [17–20] event generator. The NLO predictions for the main irreducible  $W\gamma$ +jets background and the  $Z\gamma$ +jets process are calculated using the BAUR generator [21].

For all simulated samples, showering and hadronization are implemented with PYTHIA 6, and  $\tau$  lepton decays with the TAUOLA 2.7 program [22]. The CTEQ6L [23] PDFs are used to model the proton PDFs for the LO generators, while CT10 [24] is used for the NLO generators. The top quark mass is set to 172.5 GeV.

The response of the CMS detector is simulated with GEANT4 [25], and all simulated events are reconstructed and analyzed using the standard CMS software. The MC simulated events are weighted to reproduce the trigger and reconstruction efficiencies measured in data. The PYTHIA 6 generator is used to simulate the presence of additional proton-proton interactions in the same or nearby proton bunch crossings (pileup). The distribution of the number of pileup events in the simulation is weighted to match that in data.

### 4 Event selection and reconstruction of signal

The signal events are generally characterized by the presence of an isolated energetic photon, a muon, significant missing transverse momentum, and one  $b$  quark jet ( $b$  jet). The presence of an isolated muon and an isolated photon provides a clean signature for the signal. Events are initially selected with a single-muon trigger, requiring a muon with a minimum  $p_T$  of 24 GeV within the pseudorapidity range  $|\eta| < 2.1$ . Events are also required to have at least one well reconstructed  $pp$  interaction vertex candidate [26]. When more than one interaction vertex is found in an event, the one with the highest  $\sum p_T^2$  of its associated charged-particle tracks is called the primary vertex and selected for further analysis. The track associated with the muon candidate is required to be consistent with a particle coming from the primary vertex.

A particle-flow algorithm (PF) is used to reconstruct single-particle candidates, combining information from all subdetectors [27, 28]. The muon candidates are reconstructed by matching the information for tracks in the silicon tracker and the muon system. The muon candidates are required to have  $p_T > 26 \text{ GeV}$  and  $|\eta| < 2.1$ . An accepted muon is required to have a relative isolation  $I_{\text{rel}} < 0.12$ , where  $I_{\text{rel}}$  is defined as the sum of the scalar  $p_T$  of all charged (except the muon candidate) and neutral PF candidates inside a cone of size  $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} < 0.4$  around the muon direction, divided by the muon  $p_T$ , where  $\Delta\eta$  and  $\Delta\phi$  are the differences in the pseudorapidity and azimuthal angle between the directions of the PF candidate and the muon. To remove the contribution from pileup, the charged particles included in the calcula-

tion of  $I_{\text{rel}}$  are required to originate from the same vertex as the muon. Based on the average deposited energy density of neutral particles from pileup, a correction is applied to the neutral component in the isolation cone. One muon candidate is required in each event, and events with additional muon candidates with  $p_T > 10 \text{ GeV}$ ,  $|\eta| < 2.5$ , and  $I_{\text{rel}} < 0.2$  are discarded.

Photon candidates with significant energy deposition in the ECAL are required to have a  $p_T > 50 \text{ GeV}$ , with  $|\eta| < 2.5$ , but be outside of the transition region between the ECAL barrel and endcaps,  $1.44 < |\eta| < 1.56$ .

The isolation of photon candidates is defined using the following criteria: the ratio of the hadronic energy  $H$  to the total electromagnetic energy  $E$  ( $H/E$ ) inside a cone of size  $\Delta R < 0.15$  around the crystal containing the largest energy is required to be less than 0.05; the second moment of the electromagnetic shower in  $\eta$  ( $\sigma_{\eta\eta}$ ) [29] is required to be less than 0.011 (0.031) in the barrel (endcaps). Separate charged- and neutral-hadron isolation criteria, defined as the scalar sum of the  $p_T$  of all charged- or neutral-hadron PF candidates inside a cone of size  $\Delta R < 0.3$  around the photon candidate, are applied. For the barrel, charged- and neutral-hadron isolation values are required to be less than 0.7 GeV and  $0.4 + 0.04 p_T^\gamma$ , while for the endcaps they are required to be less than 0.5 GeV and  $1.5 + 0.04 p_T^\gamma$  GeV, respectively, where  $p_T^\gamma$  is the transverse momentum of the photon candidate. The isolation criteria are corrected for additional interactions in the same bunch crossing [30]. A pixel detector track veto is employed to minimize the misidentification of an electron as a photon. Events with exactly one photon candidate are selected for further analysis.

Events with one or more electron candidates that pass loose selection requirements of  $p_T > 20 \text{ GeV}$ ,  $|\eta| < 2.5$ , and  $I_{\text{rel}} < 0.15$  are rejected. The electron  $I_{\text{rel}}$  is defined in a manner similar to that for muons, using an isolation cone size of  $\Delta R < 0.3$ .

Jets are clustered from the reconstructed PF candidates, using the infrared- and collinear-safe anti- $k_T$  algorithm with a distance parameter of 0.5 [31]. The charged hadrons originating from pileup interactions are excluded from the clustered PF candidates, and the remaining contributions from neutral particles are taken into account using a jet-area-based correction [30]. The momentum of a jet is defined as the vector sum of the momenta of all particles in the jet, and corrections to the jet energy are applied as a function of the jet  $p_T$  and  $\eta$  [32]. Only jets with  $p_T > 30 \text{ GeV}$  and  $|\eta| < 2.5$  are considered in the analysis.

The combined secondary vertex (CSV) algorithm [33, 34] is used to identify jets originating from the hadronization of  $b$  quarks. The algorithm combines the information from the secondary vertex and track impact parameters into a likelihood discriminant, whose output distinguishes between  $b$  jets and light-flavor jets. The chosen cutoff on the value of the discriminant corresponds to a  $b$  tagging efficiency of about 70%, while the misidentification probability is  $\approx 18\%$  for  $c$  jets, and  $\approx 1.5\%$  for other jets [33, 34].

To reduce the background from  $t\bar{t}$  and  $t\bar{t} + \gamma$  processes, events with more than one identified  $b$  jet are rejected. In events with no  $b$ -tagged jet, the jet with the largest value of the  $b$  tag discriminant is chosen as the  $b$  jet candidate. The missing transverse momentum vector,  $\vec{p}_T^{\text{miss}}$ , is defined as the negative vectorial sum of the momentum in the transverse plane of all PF objects. Its magnitude,  $p_T^{\text{miss}}$ , is required to be greater than 30 GeV. The direction of the photon candidate is required to be separated from the directions of the muon and  $b$  jet candidates by  $\Delta R(\mu, \gamma) > 0.7$  and  $\Delta R(b \text{ jet}, \gamma) > 0.7$ .

The top quark kinematic properties are reconstructed using the muon and  $b$  jet four-momenta and  $\vec{p}_T^{\text{miss}}$ . The  $p_T$  of the undetected neutrino is assumed to be equal to the magnitude of  $\vec{p}_T^{\text{miss}}$ , while its longitudinal component is obtained by constraining the invariant mass of the neutrino

and muon to the world-average value of the  $W$  boson mass [35]. When the resulting quadratic equation has two real solutions, the one with the smaller absolute value of the longitudinal component of the neutrino momentum is taken [36]. When the solution is complex, the real part is considered as the longitudinal  $z$  component of the neutrino momentum. The top quark candidate is reconstructed by combining the reconstructed  $W$  boson and the  $b$  jet candidate. Events with a reconstructed top quark invariant mass  $m_{\mu\nu b}$  within 130 to 220 GeV are selected for further analysis. After all the selection criteria, signal efficiencies of 1.8% and 2.4% are achieved from simulation for  $t\gamma$  and  $tc\gamma$  signal events, respectively.

## 5 Background estimation

The main background contributions arise from  $W\gamma$ +jets and  $W$  + jets events, where the  $W$  + jets background can mimic the signal when a jet is misidentified as a photon. The  $W\gamma$ +jets and  $W$  + jets backgrounds are estimated from data, while estimates for the backgrounds from single top quark ( $tq$ -,  $tb$ -, and  $tW$ -channel),  $t + \gamma$ ,  $t\bar{t}$ ,  $t\bar{t} + \gamma$ ,  $Z + \gamma$ +jets, Drell–Yan,  $WW\gamma$  + jets, and diboson backgrounds are calculated from the numbers of simulated events passing the event selection, scaled to their theoretical cross sections.

The contributions from the  $W$  + jets and  $W\gamma$  + jets backgrounds are estimated from data using a neural network (NN) discriminant formed from a combination of several variables: the  $p_T$  of the photon and jet candidates, the cosine of the angle between the momenta of the  $W$  boson and photon candidate, the azimuthal angle between the momentum of the photon candidate and the missing transverse momentum, and  $H/E$ . The NN is trained to distinguish these two sources of background and its output is parametrized as:

$$F(x_{\text{NN}}) = c_{Wj}S_{Wj}(x_{\text{NN}}) + c_{W\gamma j}S_{W\gamma j}(x_{\text{NN}}) + bB(x_{\text{NN}}), \quad (2)$$

where  $x_{\text{NN}}$  is the neural network output,  $S_{Wj}(x_{\text{NN}})$ ,  $S_{W\gamma j}(x_{\text{NN}})$ , and  $B(x_{\text{NN}})$  are, respectively, the normalized distributions for  $W$  + jets,  $W\gamma$  + jets, and the sum of all other backgrounds, and  $c_{Wj}$ ,  $c_{W\gamma j}$ , and  $b$  are the corresponding fractions of each distribution. From previous limits, it is known that any signal contribution will be small and is not included in Eq. 2. The effect of its possible presence is accounted for as a systematic uncertainty. The parametrization in Eq. 2 is fit to the data, leaving the  $W$  + jets and  $W\gamma$  + jets normalizations as free parameters. Both the normalization and the distribution in the sum of all other backgrounds, i.e., the  $b$  and  $B(x_{\text{NN}})$  terms, are obtained from simulation. The distribution for  $W$  + jets,  $S_{Wj}(x_{\text{NN}})$ , is obtained from data in a control region defined by requiring photons with wide electromagnetic showers ( $\sigma_{\eta\eta} > 0.011$  for the barrel and  $\sigma_{\eta\eta} > 0.031$  for the endcap), and no  $b$ -tagged jets, while keeping all other selection criteria the same as in the signal region. The requirement of no  $b$ -tagged jets ensures a high content of  $W$  + jets, suppressing thereby the  $t\bar{t}$  and single top quark contribution. The distribution for  $W\gamma$  + jets,  $S_{W\gamma j}(x_{\text{NN}})$ , is obtained from simulation. The numbers of  $W$  + jets and  $W\gamma$  + jets events are determined from the fit to the NN output distribution.

The fit results are taken as central values for the analysis, and are assigned uncertainties that reflect the differences obtained when varying the control region definition. Additionally, an uncertainty is assigned accounting for the limited knowledge of the contaminations from other SM backgrounds in the control sample, estimated through a comparison with the results after subtracting their expectations from simulation. To take into account the uncertainties coming from the theoretical predictions of the cross sections for the simulated backgrounds, the individual cross sections are each varied by  $\pm 30\%$  [37–39] and the differences in the fitted results with respect to the nominal fit are added in quadrature.

A total of 1794 events are selected in data and, assuming no contribution from FCNC,  $1805 \pm 80$  events are expected, where the uncertainty is statistical. The expected amount of SM background is dominated by the  $W\gamma$  + jets process, amounting to 57% of the total. The contributions of  $W$  + jets,  $t\bar{t}$ , and  $Z\gamma$  + jets events are 16%, 8%, and 7% of the total background events, respectively. The remaining background events originate from  $t+\gamma$ ,  $t\bar{t}+\gamma$ , single top quark ( $tq+tb+tW$ ),  $WW\gamma$  + jets, and diboson production.

## 6 Signal extraction

Several discriminant variables are used to distinguish the signal from the SM backgrounds. To achieve the best discriminating power, a multivariate classification, based on boosted decision trees (BDT) [40, 41], is used. One BDT is used for the  $tu\gamma$  channel and another for the  $tc\gamma$  channel to take advantage of the slight differences in their production. For the  $tu\gamma$  signal, the asymmetry between the top and anti-top quark rates translates into a lepton charge asymmetry. The lepton charge is therefore used as an input in training the BDT for the  $tu\gamma$  signal. Eight variables are chosen to construct the two BDTs. The BDT input variables are: (i)  $p_T$  of the photon candidate, (ii)  $b$  tagging discriminant, (iii)  $p_T$  of the  $b$  jet, (iv)  $p_T$  of the muon (only for  $tc\gamma$ ), (v)  $\cos(\vec{p}_t, \vec{p}_\gamma)$ , the cosine of the angle between the direction of the reconstructed top quark and photon, (vi)  $\Delta R(b \text{ jet}, \gamma)$ , (vii)  $\Delta R(\mu, \gamma)$ , (viii) lepton charge (only for  $tu\gamma$ ), and (ix) jet multiplicity.

The  $p_T$  of the photon candidate is the most important variable for separating signal from background. The  $p_T$  of the muon does not contribute significantly to the discrimination of the  $tu\gamma$  signal, and is therefore not used in this case. Each BDT is trained using simulated signal (either  $tu\gamma$  or  $tc\gamma$ ) and  $W\gamma$  + jets,  $t\bar{t}$ , and diboson background events. The distributions used as input to the BDT are obtained from data for  $W\gamma$  + jets and  $W$  + jets and from simulation for the remaining background contributions. The  $W$  + jets distributions are obtained from the same control region as used for the NN inputs. Events with a reconstructed top quark mass in the sideband region defined as  $m_{\mu\nu b} > 220 \text{ GeV}$  or  $m_{\mu\nu b} < 130 \text{ GeV}$  are used to obtain the  $W\gamma$  + jets distributions. The sideband region is enriched in  $W\gamma$  + jets, with about 35% contamination from other background sources. This contamination is subtracted using an estimate from data for the  $W$  + jets contribution and MC predictions for the remaining background sources.

Figure 2 shows the distributions of some of the BDT input variables for the  $tu\gamma$  signal and SM background. Figure 3 shows the BDT output distributions for data, the estimated background, and the  $tu\gamma$  and  $tc\gamma$  signals. As described above, the  $W\gamma$  + jets and  $W$  + jets distributions and their normalizations are estimated from data, while the remaining background contributions are obtained from simulation. The signal shapes are normalized to a cross section of 1 pb for showing the expected signal distributions in the figures. The vertical bars indicate the statistical uncertainty. The hatched band shows the contribution of the statistical and systematic uncertainties added in quadrature, with the dominant source being the statistical uncertainty in the estimation of the number of  $W$  + jets and  $W\gamma$  + jets events in data.

## 7 Systematic uncertainties

The effect on the signal and SM background expectations from different systematic sources is discussed below.

**Instrumental uncertainties:** The uncertainties in the trigger efficiency [42], photon [43] and lepton [44] selection efficiencies, jet energy scale and resolution, missing transverse mo-



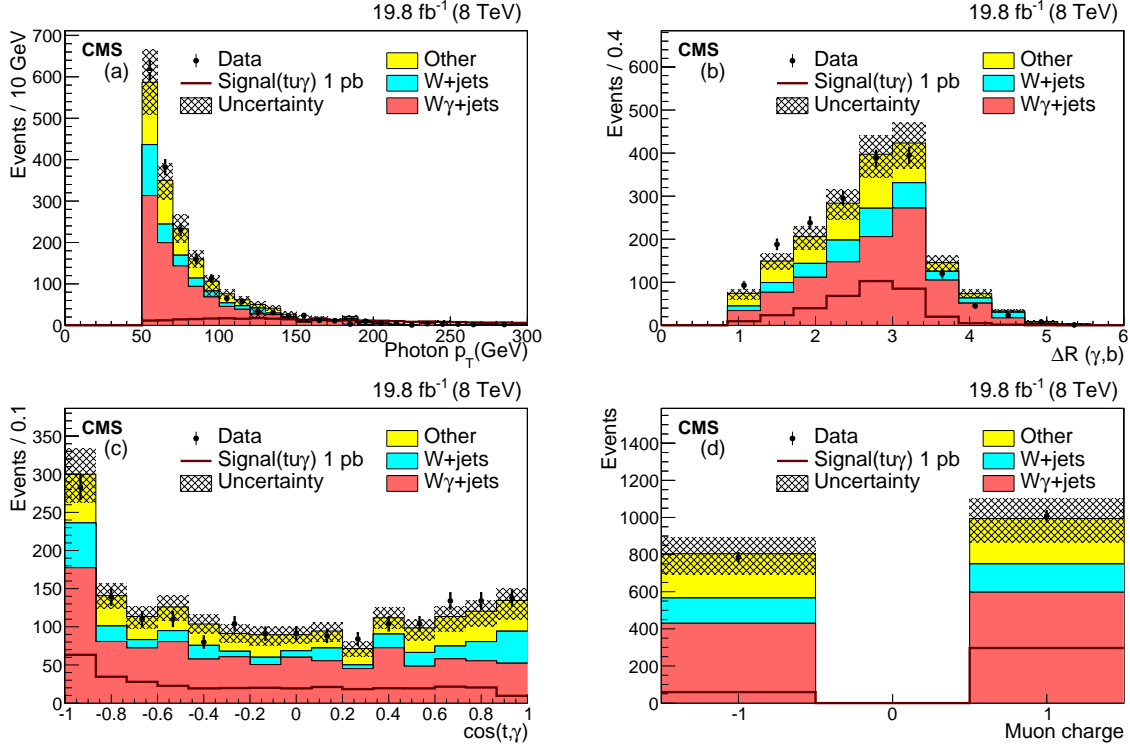


Figure 2: Distributions of some of the input variables to the BDT: (a)  $p_T$  of the photon, (b)  $\Delta R(\gamma, b)$ , (c)  $\cos(t, \gamma)$ , and (d) muon charge after the final event selection for data (points), the expected  $tu\gamma$  signal (solid line), and background (histograms). The  $tu\gamma$  signal distributions are normalized to a cross section of 1 pb. The vertical bars on the points show the statistical uncertainties in the data. The hatched band shows the sum of the statistical and systematic uncertainties in the estimated background combined in quadrature.

momentum [32], and the modeling of pileup are propagated to the uncertainties in the signal and SM background expectations. The uncertainty in modeling the pileup is estimated by changing the total inelastic proton-proton cross section by  $\pm 5\%$  [45]. The uncertainty coming from the photon energy scale is estimated by changing the photon energy in simulation by  $\pm 1\%$  in the ECAL barrel and  $\pm 3\%$  in the endcaps [43]. The  $p_T$ - and  $\eta$ -dependent uncertainties in the b jet identification efficiencies and misidentification (mistag) rates are implemented as in Ref. [33]. The systematic uncertainty in the measured integrated luminosity is estimated to be 2.6% [46]. Among the instrumental uncertainties, the luminosity uncertainty only affects the normalization, while the uncertainties from the trigger, lepton and photon selection efficiencies, b tagging, jet energy scale and resolution, and pileup also affect the BDT discriminant output distributions for signal and background.

**Theoretical uncertainties:** The uncertainty from the choice of PDF is determined according to the PDF4LHC prescription [47, 48] using the MSTW2008 [49] and NNPDF [50] PDFs. The uncertainty from the factorization and renormalization scales is evaluated by comparing simulated samples, produced using factorization and renormalization scales multiplied and divided by a factor of two relative to their standard values (top quark mass). A conservative estimate of the uncertainty owing to the top quark mass used in the simulation is obtained by producing simulated samples with the top quark mass shifted by  $\pm 2$  GeV. The uncertainties in the PDF, renormalization and factorization scales, and top quark mass affect both the predicted BDT distributions and the normalizations. An uncertainty

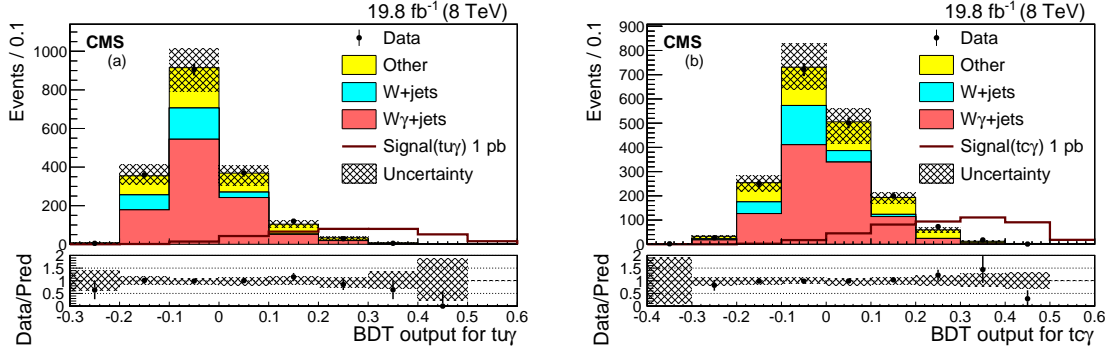


Figure 3: The BDT output distributions for the data (points), the backgrounds (histograms), and the expected  $tu\gamma$  (a) and  $tc\gamma$  (b) signals (solid lines). The  $tu\gamma$  and  $tc\gamma$  signal distributions are normalized to a cross section of 1 pb. The vertical bars on the points give the statistical uncertainties. The hatched band shows the sum of the statistical and systematic uncertainties in the predicted background distributions combined in quadrature. The lower plots show the ratio of the data to the SM prediction.

of 5% in the signal rate is estimated from the NLO QCD corrections [12]. This uncertainty is assumed not to affect the signal distributions.

**Normalization of the background:** The uncertainties described in Section 5 for the estimated  $W\gamma + \text{jets}$  and  $W + \text{jets}$  backgrounds are found to be 17% and 23%, respectively. The uncertainties in the normalization of all other backgrounds are found to be 30% [37–39].

## 8 Upper limits on anomalous couplings

No evidence is observed for anomalous single top quark production in association with a photon in the BDT output distributions shown in Fig. 3. These results are used to set an upper limit on this process, as well as on the anomalous couplings  $\kappa_{tu\gamma}$  and  $\kappa_{tc\gamma}$ . The limits are calculated using the modified frequentist approach [51, 52] that is implemented in the THETA package [53]. In this approach, a binned maximum-likelihood method is used for the BDT output distribution, which includes all systematic uncertainties described in the previous section as nuisance parameters. The NLO QCD corrections to the production of a single top quark plus a photon through FCNC processes are sizable and depend on the photon  $p_T$  requirement [12]. Upper limits on the cross sections are presented both with and without NLO QCD corrections. We use a  $k$  factor  $k = \sigma_{\text{NLO}}/\sigma_{\text{LO}} = 1.375$  to go from LO to NLO, corresponding to a minimum photon  $p_T$  of 50 GeV [12].

The 95% CL upper limits on the number of events observed are 9.1 and 16.0 for the  $tu\gamma$  and  $tc\gamma$  signals, respectively. The 95% CL upper limits on the product of the LO signal cross sections and the leptonic branching fraction of the W boson are  $\sigma_{tu\gamma} \mathcal{B}(t \rightarrow Wb \rightarrow b\ell\nu_\ell) < 25$  fb and  $\sigma_{tc\gamma} \mathcal{B}(t \rightarrow Wb \rightarrow b\ell\nu_\ell) < 34$  fb. The corresponding upper limits for the NLO calculations are  $\sigma_{tu\gamma} \mathcal{B}(t \rightarrow Wb \rightarrow b\ell\nu_\ell) < 26$  fb and  $\sigma_{tc\gamma} \mathcal{B}(t \rightarrow Wb \rightarrow b\ell\nu_\ell) < 37$  fb. The expected limits and the one and two standard deviation limits on  $\sigma_{tu\gamma} \mathcal{B}(t \rightarrow Wb \rightarrow b\ell\nu_\ell)$  and  $\sigma_{tc\gamma} \mathcal{B}(t \rightarrow Wb \rightarrow b\ell\nu_\ell)$  at LO and NLO are presented in Table 1. These results can be translated into upper limits on the anomalous couplings  $\kappa_{tu\gamma}$  and  $\kappa_{tc\gamma}$  and on the branching fractions  $\mathcal{B}(t \rightarrow u + \gamma)$  and  $\mathcal{B}(t \rightarrow c + \gamma)$  using the theoretical expectations [54]. The 95% CL upper bounds on the anomalous couplings and branching fractions with and without including the NLO QCD corrections to the signal cross section are presented in Table 1, along with the expected limits. The one and two standard deviation ranges of the LO and NLO expected limits on the

Table 1: The expected and observed 95% CL upper limits on the FCNC  $t\bar{u}\gamma$  and  $t\bar{c}\gamma$  cross sections times branching fraction  $\mathcal{B}(t \rightarrow Wb \rightarrow b\ell\nu_\ell)$ , the anomalous couplings  $\kappa_{t\bar{u}\gamma}$  and  $\kappa_{t\bar{c}\gamma}$ , and the corresponding branching fractions  $\mathcal{B}(t \rightarrow u\gamma)$  and  $\mathcal{B}(t \rightarrow c\gamma)$  at LO and NLO are given. The one and two standard deviation ( $\sigma$ ) ranges on the LO and NLO expected limits are also presented.

	Exp. limit (LO)	$\pm 1\sigma$ (exp. limit)	$\pm 2\sigma$ (exp. limit)	Obs. limit (LO)
$\sigma_{t\bar{u}\gamma} \mathcal{B}$ (fb)	40	30–56	23–78	25
$\sigma_{t\bar{c}\gamma} \mathcal{B}$ (fb)	39	30–55	24–76	34
$\kappa_{t\bar{u}\gamma}$	0.036	0.032–0.043	0.028–0.051	0.029
$\kappa_{t\bar{c}\gamma}$	0.111	0.098–0.132	0.087–0.16	0.10
$\mathcal{B}(t \rightarrow u\gamma)$	$2.7 \times 10^{-4}$	$(2.0 - 3.8) \times 10^{-4}$	$(1.6 - 5.4) \times 10^{-4}$	$1.7 \times 10^{-4}$
$\mathcal{B}(t \rightarrow c\gamma)$	$2.5 \times 10^{-3}$	$(1.9 - 3.6) \times 10^{-3}$	$(1.5 - 4.9) \times 10^{-3}$	$2.2 \times 10^{-3}$
	Exp. limit (NLO)	$\pm 1\sigma$ (exp. limit)	$\pm 2\sigma$ (exp. limit)	Obs. limit (NLO)
$\sigma_{t\bar{u}\gamma} \mathcal{B}$ (fb)	39	30–58	25–84	26
$\sigma_{t\bar{c}\gamma} \mathcal{B}$ (fb)	42	29–59	22–86	37
$\kappa_{t\bar{u}\gamma}$	0.031	0.026–0.037	0.024–0.086	0.025
$\kappa_{t\bar{c}\gamma}$	0.098	0.082–0.12	0.071–0.140	0.091
$\mathcal{B}(t \rightarrow u\gamma)$	$1.9 \times 10^{-4}$	$(1.4 - 2.9) \times 10^{-4}$	$(1.2 - 4.2) \times 10^{-4}$	$1.3 \times 10^{-4}$
$\mathcal{B}(t \rightarrow c\gamma)$	$2.0 \times 10^{-3}$	$(1.3 - 2.7) \times 10^{-3}$	$(1.0 - 4.0) \times 10^{-3}$	$1.7 \times 10^{-3}$

anomalous couplings and branching fractions are also shown in Table 1. The measured 95% CL upper limits on  $\mathcal{B}(t \rightarrow qZ)$  versus  $\mathcal{B}(t \rightarrow q\gamma)$  from the L3 [5], ZEUS [6], H1 [7], D0 [55], CDF [56], ATLAS [57], and CMS [58] experiments, as well as the results of this analysis, are presented in Fig. 4.

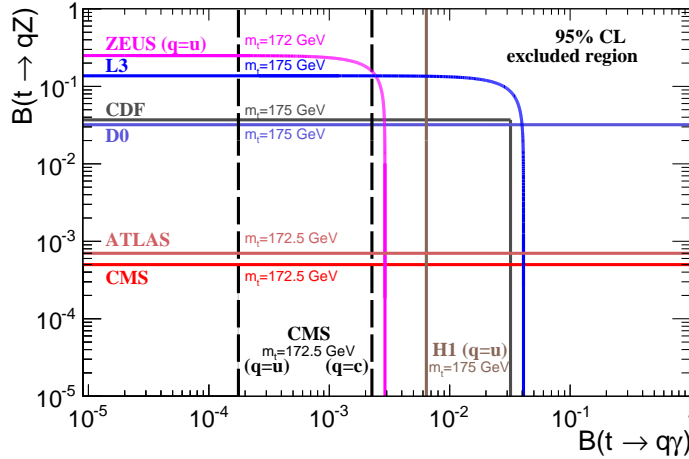


Figure 4: The measured 95% CL upper limits on  $\mathcal{B}(t \rightarrow qZ)$  versus  $\mathcal{B}(t \rightarrow q\gamma)$  from the L3 [5], ZEUS [6], H1 [7], D0 [55], CDF [8, 56], ATLAS [57], and CMS experiments [58]. The two vertical dashed lines show the results of this analysis.

Table 2 summarizes the sources of the systematic uncertainties in the expected upper limits on the signal cross sections. These are calculated as the ratio of the difference of the shifted expected limit coming from the related systematic source and the nominal expected limit.

Table 2: The sources and values of systematic uncertainties used to determine the observed and expected upper limits on the  $tu\gamma$  and  $tc\gamma$  cross sections. The values are given as a percentage of the expected upper limits. The sources are broken up into those that only affect the overall rate of signal events and those that affect both the rate and the shape of the BDT distributions.

Type	Source	$tu\gamma$ (%)	$tc\gamma$ (%)
Rate	Integrated luminosity	1.8	4
	Background normalization ( $W + \text{jets}$ )	5.6	3
	Background normalization ( $W\gamma + \text{jets}$ )	2.5	1.1
	Other background normalizations	<1	1
Rate+Shape	Trigger efficiency	2.2	0.4
	Pileup effects	7	2.3
	Lepton identification and isolation	<1	4.4
	Photon identification and isolation	1.9	4.5
	Photon energy scale	<1	3.1
	b tagging and mistag efficiency	1.1	4
	Jet energy scale	2.9	2.2
	Jet energy resolution	2.1	3.4
	PDF	3.1	<1
	Scale	1	2.4
	Top quark mass	2.5	1

## 9 Upper limits on the FCNC cross sections for a restricted phase space

Upper limits on the signal cross sections are also determined for a restricted phase-space region in which the detector is fully efficient. This removes the need to extrapolate to phase-space regions where the analysis has little or no sensitivity. The results are especially useful for comparing with theoretical models that predict enhancements in a particular phase-space region [10].

The measurement uses a simpler event-counting procedure instead of a fit to the BDT distribution. We define the fiducial cross section,  $\sigma_{\text{fid}}$ , in a volume defined for stable particles at the generator level before any interaction with the detector. This can be related to the total cross section,  $\sigma$ , through  $\sigma_{\text{fid}} = \sigma A$ , where  $A$  is the acceptance in the fiducial volume. Stable particles are characterized as particles with mean lifetimes exceeding 30 ps. The upper limit on  $\sigma_{\text{fid}}$  is obtained from the limit on  $\sigma A \epsilon$ , where  $\epsilon$  accounts for detector resolution, trigger efficiencies, and identification and isolation requirements applied in the analysis.

The leptons at the particle level are the electrons or muons originating from the decay of  $W$  bosons. The charged leptons from hadron decays are discarded, while electrons or muons from direct decays of  $\tau$  leptons are included.

Stable particles, except muons, electrons, photons and neutrinos, are used to reconstruct particle-level jets in the simulation. Jet reconstruction at the particle level is based on the anti- $k_T$  algorithm [31] with a distance parameter of 0.5. When a reconstructed jet contains a B hadron, the jet is tagged as a b jet. In events without a matched b jet, the jet with the largest  $p_T$  is used to reconstruct the decayed top quark. The  $p_T$  of the neutrinos is calculated as the magnitude of the vector sum of the  $p_T$  of each neutrino in the event, except those originating from hadron decays. From these objects, the top quark mass is calculated in order to make kinematical cuts used in the definition of the fiducial region. The fiducial region is introduced at particle level, similar to the event selection requirements, and is summarized in Table 3.

Table 3: Definition of the fiducial region.

Object	Requirement
Single muon	$p_T > 26 \text{ GeV},  \eta  < 2.1$
Veto for additional muons	$p_T > 10 \text{ GeV},  \eta  < 2.5$
Electron veto	$p_T > 20 \text{ GeV},  \eta  < 2.5$
Single photon	$p_T > 50 \text{ GeV},  \eta  < 2.5$ ( $1.44 <  \eta  < 1.56$ excluded)
At least one jet ( $N_{b \text{ jet}} < 2$ )	$p_T > 30 \text{ GeV},  \eta  < 2.5$
Missing $p_T$	$p_T^{\text{miss}} > 30 \text{ GeV}$
Muon, jets, and photons	$\Delta R(\mu, \gamma) \text{ and } \Delta R(\text{jet}, \gamma) > 0.7$
Reconstructed top quark mass	$130 < m_{\mu\nu b} < 220 \text{ GeV}$

The efficiency  $\epsilon$  is found to be 16% and 19% from simulation for the respective  $\text{tu}\gamma$  and  $\text{tc}\gamma$  events in the fiducial region. An additional fiducial region is defined by also requiring exactly one b-tagged jet in the event. The values of  $\epsilon$  are thereby reduced to 11% and 14% for the two signals, respectively.

Table 4 shows the 95% CL upper limits on the signal cross sections in the two fiducial regions for the  $\text{tu}\gamma$  and  $\text{tc}\gamma$  processes. These are calculated from the total number of selected events in data ( $N_{\text{obs}}$ ), the SM expectation ( $N_{\text{SM}}$ ), both at detector level, and the efficiency for a signal event in the fiducial region to be reconstructed at detector level. The uncertainties in the SM expectation include statistical and systematic uncertainties. The total number of observed events is decreased by a factor of approximately 6.5 after requiring exactly one identified b jet in an event, while the expected number of SM events decreases by a factor of 7. The combined relative uncertainty in the number of expected SM events increases from 12% to 19% when this b jet requirement is included.

The upper limits are calculated including a total systematic uncertainty in the signal selection efficiencies of 10%, estimated using a method similar to that described in Section 7. These are the first limits set on the anomalous  $\text{t}\gamma$  production within a restricted phase-space region.

Table 4: The total number of observed selected events at detector level in the data ( $N_{\text{obs}}$ ), the SM expectations ( $N_{\text{SM}}$ ), the efficiencies ( $\epsilon$ ), and the upper limits on the cross sections  $\sigma_{\text{fid}}$  at the 95% CL in the fiducial region for the two signal channels, without and with a requirement on the presence of a single accompanying b jet.

Fiducial region	Channel	$N_{\text{obs}}$	$N_{\text{SM}}$	$\epsilon$	$\sigma_{\text{fid}}^{95\%} \text{ (fb)}$
Basic selection (Table 3)	$\text{tu}\gamma$	1794	$1805 \pm 215$	0.16	122
	$\text{tc}\gamma$			0.19	103
Basic selection and $N_{b \text{ jet}} = 1$	$\text{tu}\gamma$	275	$258 \pm 49$	0.11	47
	$\text{tc}\gamma$			0.14	39

## 10 Summary

The result of a search for flavor changing neutral currents (FCNC) through single top quark production in association with a photon has been presented. The search is performed using proton-proton collisions at a center-of-mass energy of 8 TeV, corresponding to an integrated luminosity of  $19.8 \text{ fb}^{-1}$ , collected by the CMS detector at the LHC. The number of observed events is consistent with the SM prediction. Upper limits are set at 95% CL on the anomalous FCNC couplings of  $\kappa_{\text{tu}\gamma} < 0.025$  and  $\kappa_{\text{tc}\gamma} < 0.091$  using NLO QCD calculations. The corresponding upper limits on the branching fractions are  $\mathcal{B}(\text{t} \rightarrow \text{u}\gamma) < 1.3 \times 10^{-4}$  and  $\mathcal{B}(\text{t} \rightarrow \text{c}\gamma) < 1.7 \times 10^{-3}$ , which are the most restrictive bounds to date. Observed upper

limits on the cross section in a restricted phase space are found to be 47 fb and 39 fb at 95% CL for  $t\bar{u}\gamma$  and  $t\bar{c}\gamma$  production, respectively, when exactly one identified b jet is required in the data. These are the first results on anomalous  $t\bar{\gamma}$  production within a restricted phase-space region.

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